In-situ X-ray CT results of damage evolution in L6 ordinary chondrite meteorites

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HEMI | HOPKINS EXTREME MATERIALS INSTITUTE

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Mechanical and thermal damage characterization

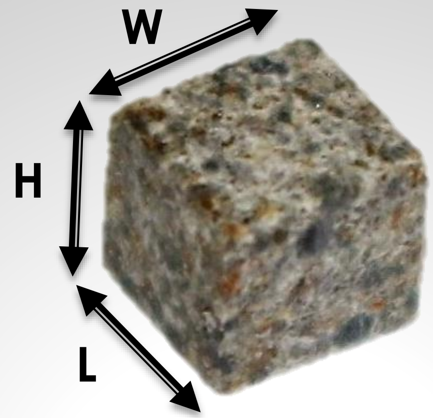
Objectives:

1. Characterize damage mechanisms as a result of the mechanical loading at a low strain rate. Microscopic damages will be evaluated at intermediate load levels.

2. Investigate damage initiation and evolution as a function of thermal cycles. Volumetric inspection at critical temperature at specific cycles will be evaluated

3. Differentiate the dominant damage mechanisms between mechanical compression and thermal loading

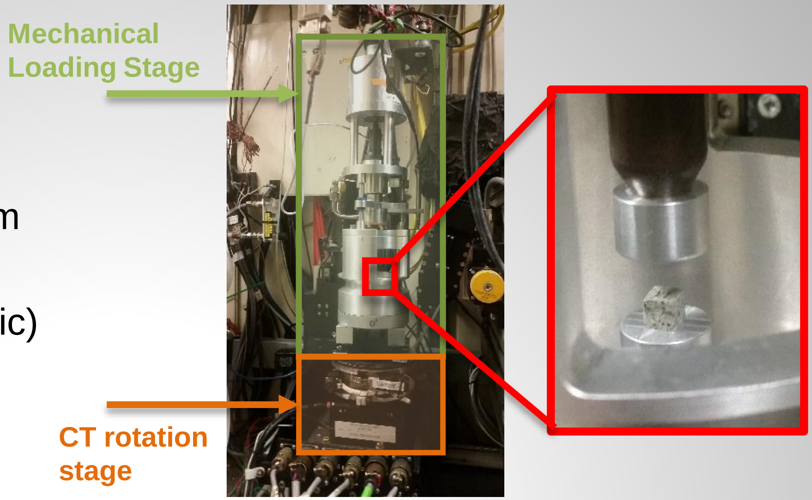
List of Grosvenor Mountain (GRO) Meteorite Samples



Sample	Mechanical Load	Thermal Fatigue	Volume HxLxW [mm³]	Density [g/cc]
GRO-B11	X		5.61x5.47x5.47	3.4673
GRO-B12*	X		6.07x5.45x5.63	3.3874
GRO-B13			6.13x5.51x5.47	3.4056
GRO-B14		X	6.19x5.5x5.75	3.3874
GRO-Chipped	X		N.A.	N.A.

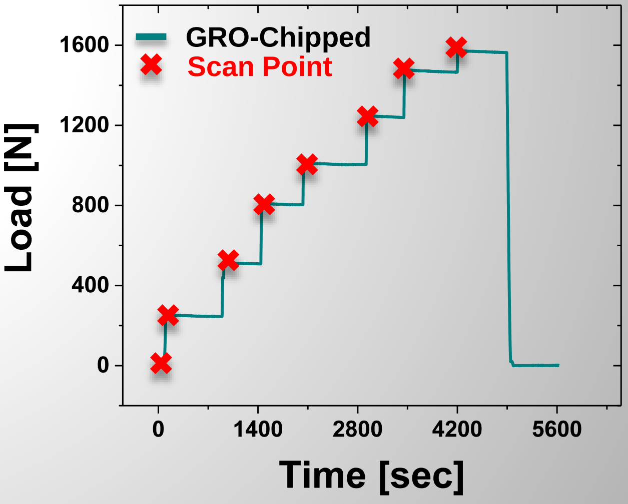
*Sample failed due to load stage instability

In-situ X-ray Compression Test Setup



- **X-ray system parameters**
  - Inspection Volume: 4.8 mm x 5 mm x 5 mm
  - Voxel Size 3.22 μm (Isotropic)
  - 30% transmission at 40 keV (Polychromatic)
  - 0-180º range with 1025 projections
  - 10 mins. per scan (Average)

- **Loading Parameters**
  - Strain rate of **10^{-3} s^{-1}** (5 μm/sec)
  - Load Cell Maximum Load 1600 N
  - Expected compression strength > 50 MPa (1250 N)
    - Samples did not fail at maximum load
  - **8 static load steps** for X-ray scanning points
    - **0N**, 250 N, 500 N, 750 N, 1000 N, 1250 N,1500 N , and **1580 N**

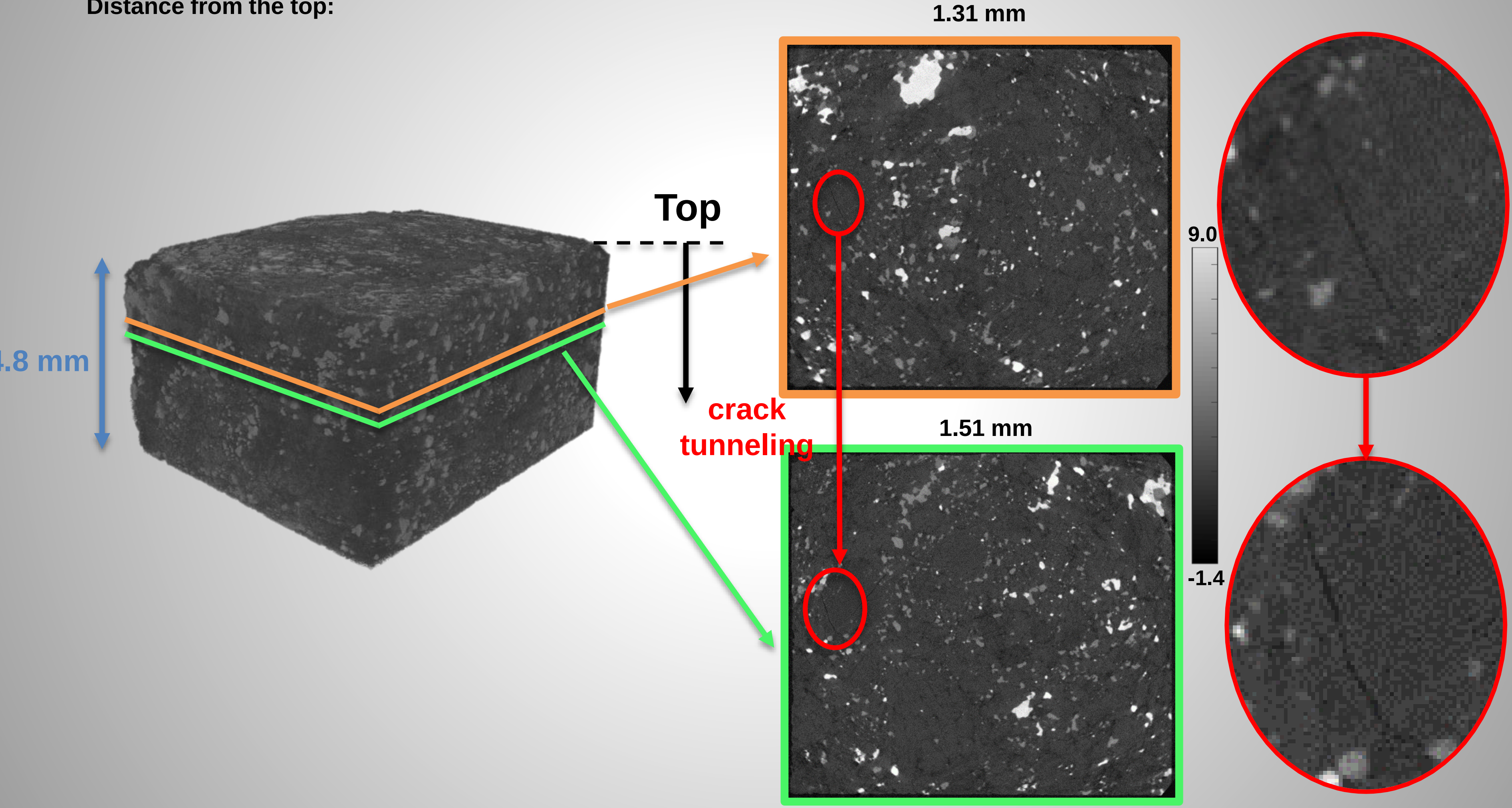


GRO-Chipped

Reference at 0 N – Existing Cracks

Cross Sections showing existing cracks inside volume

Distance from the top:

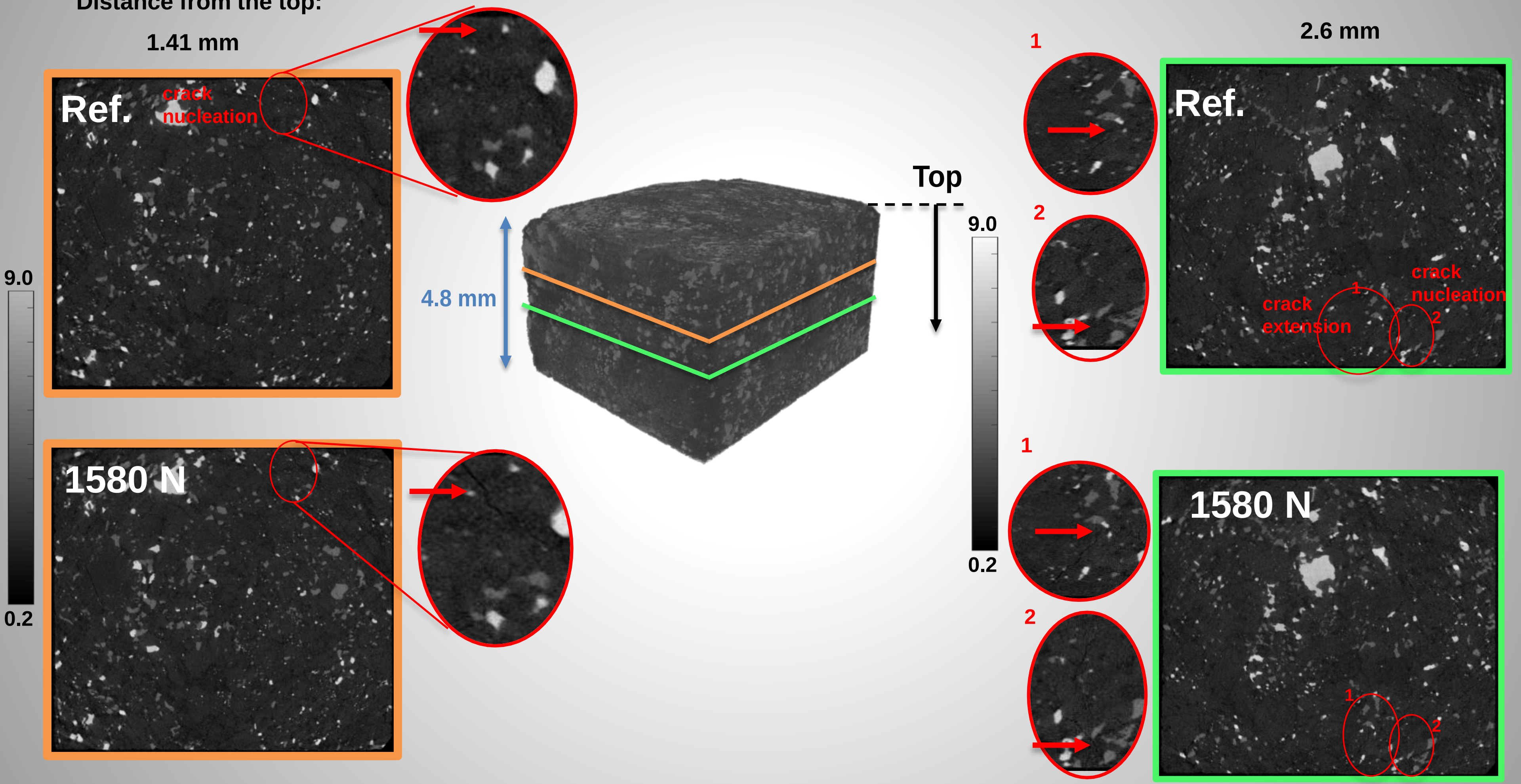


GRO-Chipped

Loaded at 1580 N

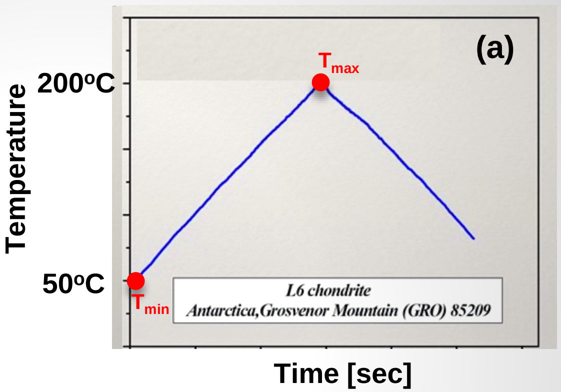
2 Cross Sections showing crack nucleation and extension

Distance from the top:



In-situ X-ray Thermal Fatigue Test Setup

- **X-ray system parameters**
    - Inspection Volume 4 x 5 x 5 mm^3 (height x length x width)
    - Voxel Size 3.22 μm (Isotropic)
    - 30% transmission at 40 keV (Polychromatic source)
    - 0-180º range with 1025 scan projections
    - 8 mins. per scan (Average)
- **Thermal Parameters**
    - Hot Plate
        - 50ºC (T_{min}) to 200ºC (T_{max}) ramp cycle
    - Scans were performed at T_{min}, T_{max} and room temperature including a reference scan
        - Scanning point at cycles: 1, 37, and 47
    - 47 cycles at 20ºC/min when heating and exponentially decaying when cooling down



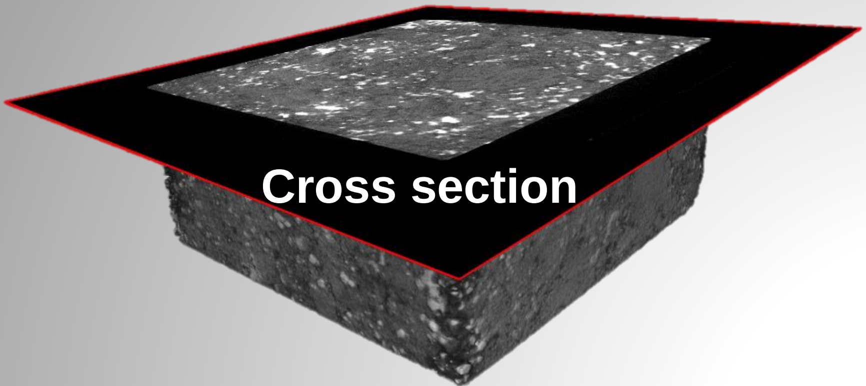
(b)

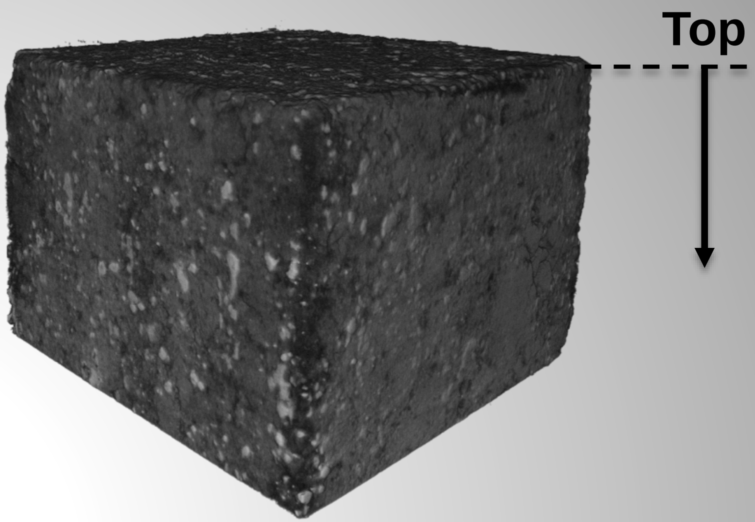
Fig. 1: (a) Single ramp temperature cycle profile [1] and (b) Thermal fatigue setup

[1] Hazeli et al. Thermal fatigue and regolith formation on airless bodies: Thermally induced crack growth in an L6 chondrite. LPS (2015)

GRO-B14

Room Temperature Reference

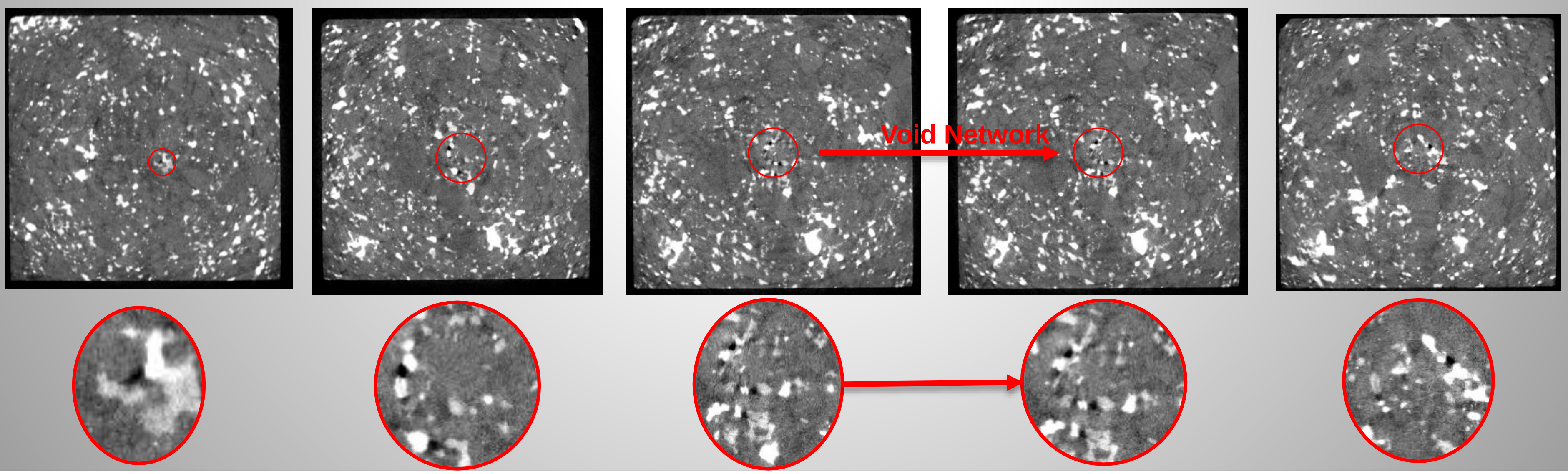




Cross Sections showing voids inside volume

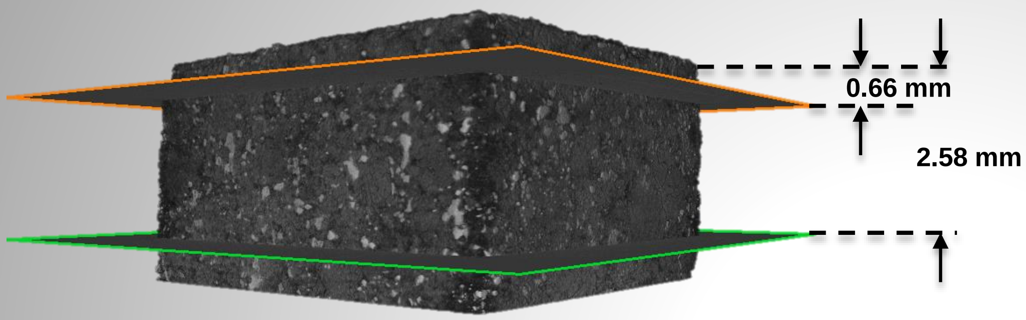
Distance from the top:

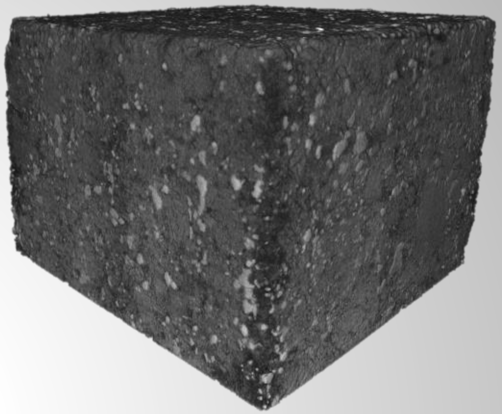
1.45 mm **2.25 mm** **2.38 mm** **2.42 mm** **2.69 mm**



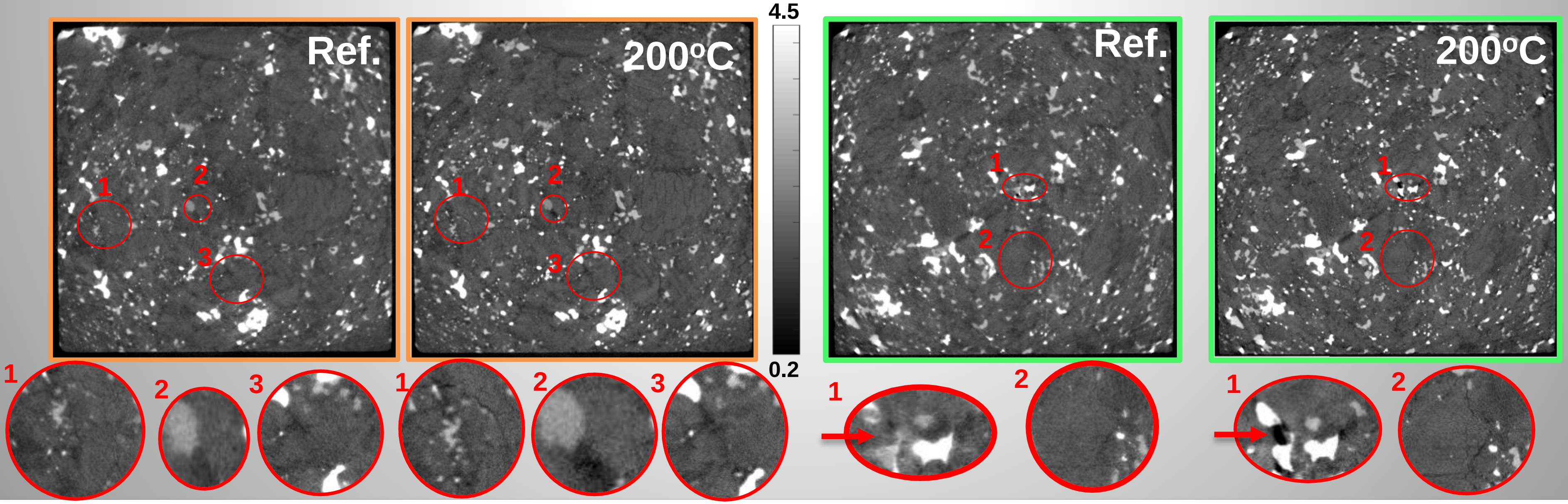
GRO-B14

Cycle 47 at 200^{o}C



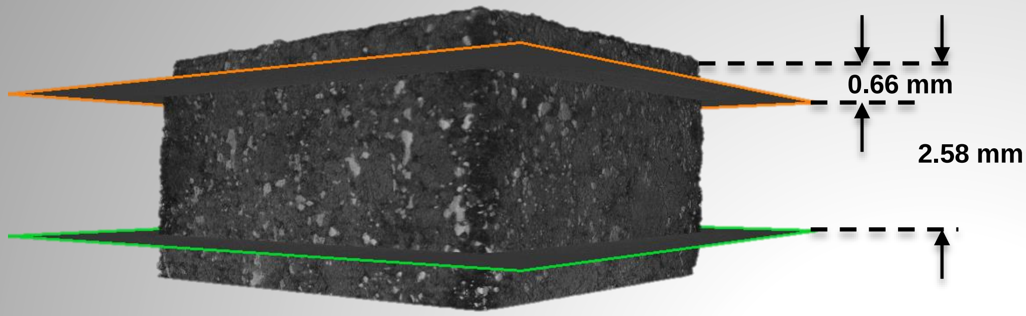


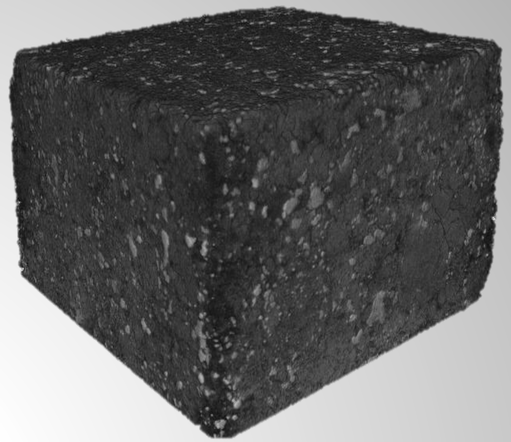
Room Temperature (RT) reference and 200^{o}C after 47 cycles Comparison



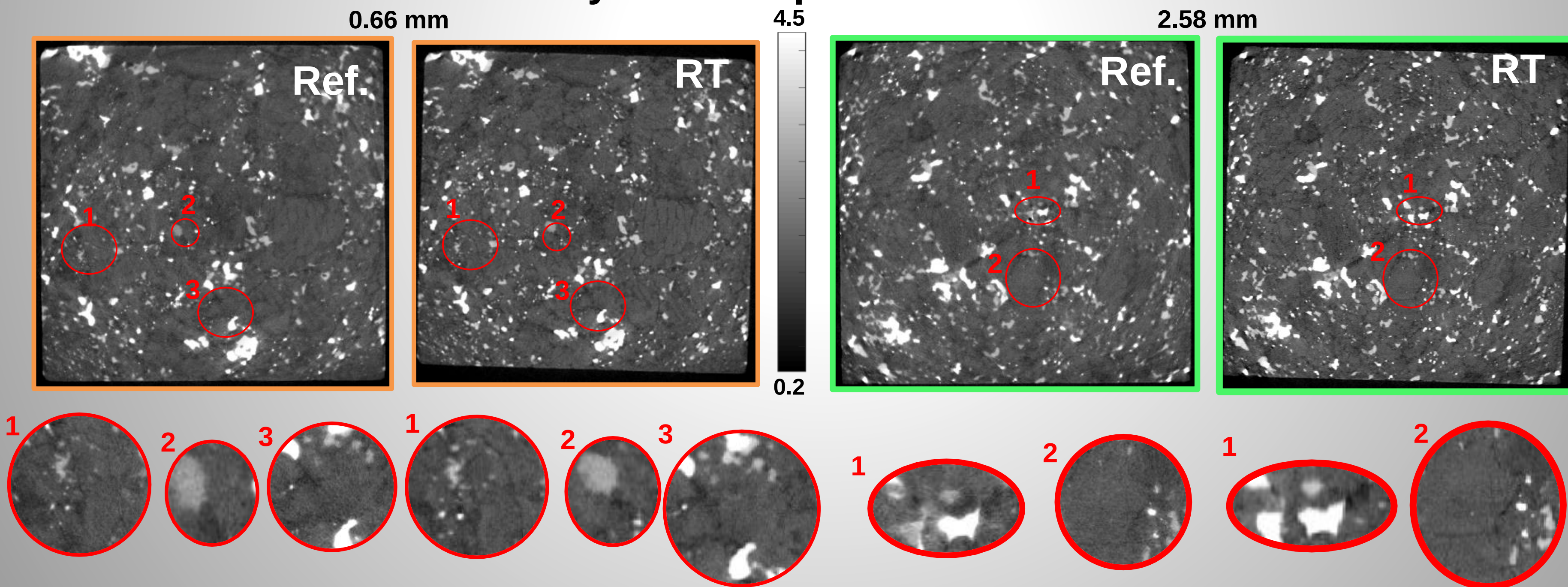
GRO-B14

Cycle 47 at Room Temperature





Reference and RT after 47 cycles Comparison



Conclusions from Qualitative Analysis

- Both GRO-Chipped and GRO-B14 had existing voids and cracks within the volume. These sites with existing damage were selected for CT images from mechanically and thermally loaded scans since they are prone to damage initiation
  - The mechanically loaded sample showed that cracks extension and nucleation occur within the lower density material (matrix-plagioclase and mafic)
  - In contrast the sample under thermal load shows that crack extension and void formation occurs nearby the inclusions
- The GRO-Chipped sample was loaded to 1580 N which resulted in a 14% compressive engineering strain, calculated using LVDT
- Based on the CT cross sectional images, the GRO-B14 sample at 200^{o}C has a thermal expansion of approximately 96 μm in height (i.e. ~1.6% engineering strain)

Future Work and Next Steps

- To image entire volume, the sample can be cut as a cylinder with a smaller height (< 4 mm) in order to avoid reconstruction artifacts
  - Note: In polychromatic mode (i.e. 40 KeV X-ray energy), the FOV is narrower due to high intensity X-ray flux

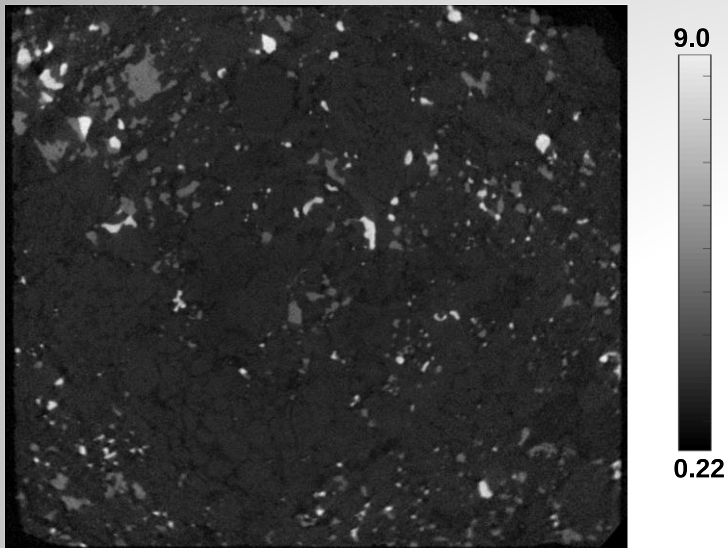
- Present this qualitative work in upcoming conferences
  - Possibly The Mineral, Metals & Materials Society 2017 Conference TMS2017 ?

- Submit a journal article
  - Wait for quantitative results?
    - Crack quantification
  - Perform Digital Volume Correlation (DVC) for mechanical and thermal strain volumetric field characterization
    - Requires image registration and contrast (i.e. more inclusions)
  - Develop a Fracture Mechanics Computational Model
    - Requires Image Segmentation to group inclusions from matrix to create Finite Element Mesh
    - Use Linear Elastic Fracture Mechanics Damage Criteria coupled with an extended Finite Element Method (XFEM), which will require DVC

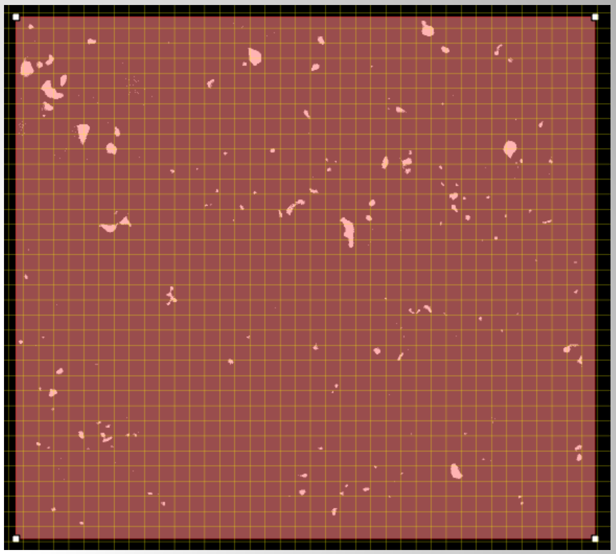
EXTRA SLIDES

DIGITAL VOLUME CORRELATION

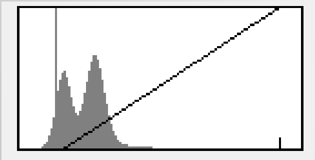
Imported tiff-files for reference



DVC facet field



Linear attenuation coefficient histogram



- Need more inclusions or truncate data around 4.5 in order to obtain more contrast. Other image analysis techniques could be attempted